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TECHNICAL NOTE

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TESTS OF AN ASYMMETRICAL BAFFLE FOR

FUEL-SLOSHING SUPPRESSION

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SUMMARY

Damping effectiveness of a new type of fuel-sloshing baffle is presented in terms of measured frequency response of a cylindrical tank undergoing forced translational motion. The results are given in the form of damping ratio, fundamental natural frequency, and coupled frequency so that the dynamic response functions which represent fuel dynamics are defined. The baffle by virtue of its asymmetrical form is shown to couple the fundamental sloshing mode with the second symmetrical mode in such a way that the effective damping is considerably higher than the damping of conventional ring-type baffles of equal area.

INTRODUCTION

The problem of damping the fundamental fuel-sloshing mode to prevent coupling with a swiveling rocket control system and structural modes has been studied in great detail in references 1, 2, 3, 4, and many others. These experiments have centered mainly around ring-type baffles for providing the needed damping but other types such as floating cans and accordion baffles were also investigated. However, as shown by reference 4, the damping effectiveness of the ring-type baffle is mainly dependent on the projected area, and baffles with variations in shape, thickness, and perforations are at best just equal in effectiveness to a flat plate with a sharp edge.

Since it appeared that no great gains could be achieved by refinement of ring-type baffles, a series of experiments were conducted on nonring type baffles in a cylindrical tank. The design philosophy for these new baffles was to transform the energy of the fundamental fuel-sloshing mode into other modes which would not couple with the control system. Some gains in damping effectiveness were reported in reference 4 for a swirl baffle which transformed the first sloshing mode into rotary motion and for semicircular plates which created a checkerboard wave on the surface.

During the course of these experiments it was noted that the fluid at the center of the tank had a persistent up and down motion at exactly twice the frequency of the first sloshing mode. Some calculations based

on reference 5 indicated that the mode in question was the second symmetrical mode. Further calculations of generalized forces indicated that the second symmetrical mode could be coupled to the fundamental sloshing mode by use of an asymmetrical baffle rather than the conventional symmetrical type. The damping effectiveness of this asymmetrical baffle, as determined from forced oscillation tests, is presented in this report. The results are given in the form of damping ratio, natural frequency, and coupled frequency so that the dynamic response functions which represent fuel dynamics are defined.

NOTATION

A_w double amplitude of test tank first sloshing mode, ft

F reaction force of tank with sloshing fluid, lb

a tank radius, ft

d depth of baffle measured from quiescent liquid surface, ft

g acceleration, ft/sec^2

h depth of fluid, ft

i imaginary number, $\sqrt{-1}$

t time, sec

m_t mass of tank, slugs

m total fluid mass, slugs

x lateral position of tank, ft, except where noted

y baffle position, positive downward

ζ damping ratio

Φ phase angle, deg

ω frequency of forced oscillation, radians/sec

ω_c frequency of tank and fluid with freedom in translation, radians/sec

ω_n natural undamped frequency of fluid with tank fixed, $n = 1, 2, 3, 4, \ldots$ (odd numbers for asymmetrical modes, even numbers for symmetrical modes), radians/sec

$\left|\frac{x}{F}\right|$ absolute value of equation (1)

TEST EQUIPMENT

The test equipment for measuring the effectiveness of fuel-sloshing dampers (see fig. 1) consisted of a 3-foot diameter tank, suspended on 16-foot cables and driven by a hydraulic servo. Instrumentation consisted of resistance-type transducers for measuring displacement at the top and bottom of the tank, and displacement of a float on the liquid surface near the tank wall and at the center of the tank. Force measurements were obtained from a strain-gage flexure link between the servo and the tank shown in figure 2. A guide was installed at the bottom of the tank to maintain translational motion.

The baffles were mounted on a thin band of metal which could be expanded mechanically to prevent gaps at the tank wall. The ring baffle is shown in figure 1 and the asymmetrical baffle of equal area is shown in figure 3.

REDUCTION OF DATA

The dynamic response functions for a cylindrical tank undergoing sinusoidal motion in translation are developed in reference 1. In terms of the notation used in this report, the response function of tank displacement to reaction force for the fundamental fluid mode is:

$$\frac{x}{F} = \frac{1 - (\omega/\omega_1)^2 + i2\zeta(\omega/\omega_1)}{(m + m_t)\omega^2 \left[1 - (\omega/\omega_c)^2 + i2\zeta(\omega/\omega_1)\right]} \tag{1}$$

where

$$\omega_c = \frac{\omega_1}{\sqrt{1 - \dfrac{2 \tanh 1.84(h/a)}{1.84(h/a)(1.84^2 - 1)(1 + m_t/m)}}}$$

which is in accordance with reference 1 except for the term m_t which was added to account for effect of tank mass. It may be seen that as tank mass or fluid depth h becomes large, the coupled frequency approaches the natural tank-fixed fluid frequency.

Damping ratios were determined at a point on the frequency response which corresponded to the natural tank-fixed frequency because the signal to noise ratio on the force gage output was highest at this point.

At $\omega = \omega_1$ the amplitude ratio is:

$$\left|\frac{x}{F}\right| = \frac{2\zeta}{(m + m_t)\omega_1^2 \sqrt{\left[1 - (\omega_1/\omega_c)^2\right]^2 + 4\zeta^2}}$$

which may be solved for ζ, giving

$$\zeta = \frac{1 - (\omega_1/\omega_c)^2}{2\sqrt{\dfrac{1}{(m + m_t)^2\omega_1^4 |x/F|^2} - 1}} \tag{2}$$

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where $|x/F|$ is the value at ω_1.

This equation was used for determining damping ratio. Values of ω_1 and ω_c were determined from the minimum and maximum peaks, respectively, of the measured frequency responses. Other values used in the equations were $h = 3$, $m = 41.1$, and $m_t = 6.3$.

A typical frequency response for the 1-1/2-inch ring is shown in figure 4. Also shown in this figure for d/a = 0.25 is the frequency response from equation (1) for the damping ratio determined from equation (2). As may be seen the measured frequency response is in good agreement with the form of equation (1). At frequencies above the coupled frequency, the measured response tends to fall below the response predicted by equation (1). This may be attributed to the reduction of amplitude of the first sloshing mode and increase in amplitudes of the higher fuel-sloshing modes, the frequencies of which are indicated on the figure. However, as may be seen from the measured frequency response, these higher modes do not appreciably alter the response from that of equation (1).

Some typical frequency responses for the asymmetrical baffle are shown in figure 5. The form of the frequency response is the same as for the ring baffle; hence, the same procedure for determination of damping ratio was used.

DISCUSSION OF DAMPING EFFECTIVENESS

The variation of damping ratio of the ring and asymmetrical baffle is shown in figure 6. The effectiveness of the asymmetrical baffle is given for three orientations of the baffle relative to the direction of oscillation. The corresponding natural frequencies and coupled frequencies are shown in figure 7 so that the transfer function (eq. (1)) is completely defined.

As may be seen from figure 6, the damping effectiveness of the asymmetrical baffle is considerably higher than the damping of the conventional ring baffle at certain depths. It should be noted that damping of symmetrically placed semicircles in reference 4 had nearly the same damping as the ring. For conditions near the peaks of these damping curves, difficulty was experienced in exciting the fundamental fuel-sloshing mode. Some free-oscillation tests were made in this region and it was found that, when the tank was released, the fundamental asymmetrical mode would immediately break up into the symmetrical mode at double the frequency. For this reason, damping could not be determined from decay of the surface wave. However, some free-oscillation tests with the tank fixed were made, and damping values determined from decay of side force were in substantial agreement with those shown in figure 6. The values on the curve are the lowest obtained from several runs.

The damping effectiveness of all the baffles drops off as the surface is approached, and the baffle is out of the liquid during part of the cycle. For $d/a = 0$, the scatter in damping ratio obtained from different runs is large because the surface waves are irregular and vary with the conditions of wave build-up. Values on the figure are the lowest obtained from a number of runs. It appears that the ring baffle is a more effective damper near the surface. However, the over-all effectiveness of the asymmetrical baffle is considerably higher than that of a ring of equal area. In figure 7, it may be seen that the asymmetrical baffle also causes the shift in ω_1 and ω_c to occur at a greater depth than the ring baffle.

As mentioned in the introduction, the asymmetrical baffle was designed to excite the second symmetrical mode in order to transmit energy from the first sloshing mode into a form which would not couple with the control system. The basis for this design was twofold: First, an analysis of the harmonic content of force generated by an oscillating plate in two-dimensional tests, reported in reference 4, indicated a large component at double the frequency of the fundamental oscillating frequency. Typical harmonic content of the force on a plate which is oscillating at frequency ω is shown in figure 8. Values shown represent the first, second, and third terms of a Fourier series expansion of the measured time history of the force. Second, the generalized force of the second harmonic baffle force output which excites the second symmetrical mode (ω_4), shown in figure 9, tends to be cancelled if a baffle is symmetrical. However, no such cancellation takes place if the baffle is only on one side, that is, asymmetrical. The resultant excitation of the symmetrical mode by these baffles is most striking as may be seen in figure 10. The damping obtained for this condition is indicated in figure 6.

Excitation of the second symmetrical mode occurs to some extent for all types of baffles, and the frequency of the mode was measured by the center displacement pickup shown in figure 3. The frequency is in

agreement with that predicted by Lamb in reference 5. Some measurements were also made with a pressure cell located 18 inches below the surface, and it was found that the pressure output was predominantly at the frequency of the second symmetrical mode even when the amplitude of the first asymmetrical mode was much greater. An examination of lines of equal potential of the two modes indicated that the pressure cell is more sensitive to the second symmetrical mode than the first asymmetrical mode for this location. This offers a possible explanation for the double frequency pressures which were noted in reference 6. It also indicates that caution should be observed in using pressure cells for measurement of the fundamental fuel-sloshing mode.

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In applications of these baffles, larger excitation of the second symmetrical mode is to be expected. Because of its symmetry and high frequency, this mode should have little or no effect on the control system, but it may couple with structural modes, and this possibility should be considered. The principle of coupling the fundamental fluid-sloshing mode to a fluid mode of double frequency in order to achieve higher damping should be applicable to any tank in which a double frequency mode occurs. The exact mechanism of the coupling which occurs with these baffles is not completely understood. Consequently, it seems likely that other asymmetrical baffles may be even more effective than the semicircles used here.

CONCLUSIONS

Evaluation of damping measurements of an asymmetrical baffle by forced oscillation of a cylindrical tank in translation has led to the following conclusions:

1. The new asymmetrical baffle is substantially more effective as a fuel damper than conventional ring-type baffles of equal area.

2. The second symmetrical fluid mode which occurs at double the frequency of the fundamental fuel-sloshing mode is excited by fuel sloshing at the fundamental frequency. The degree of excitation of this mode has an important effect on the apparent damping of the fundamental mode and pressure measurements at the tank wall.

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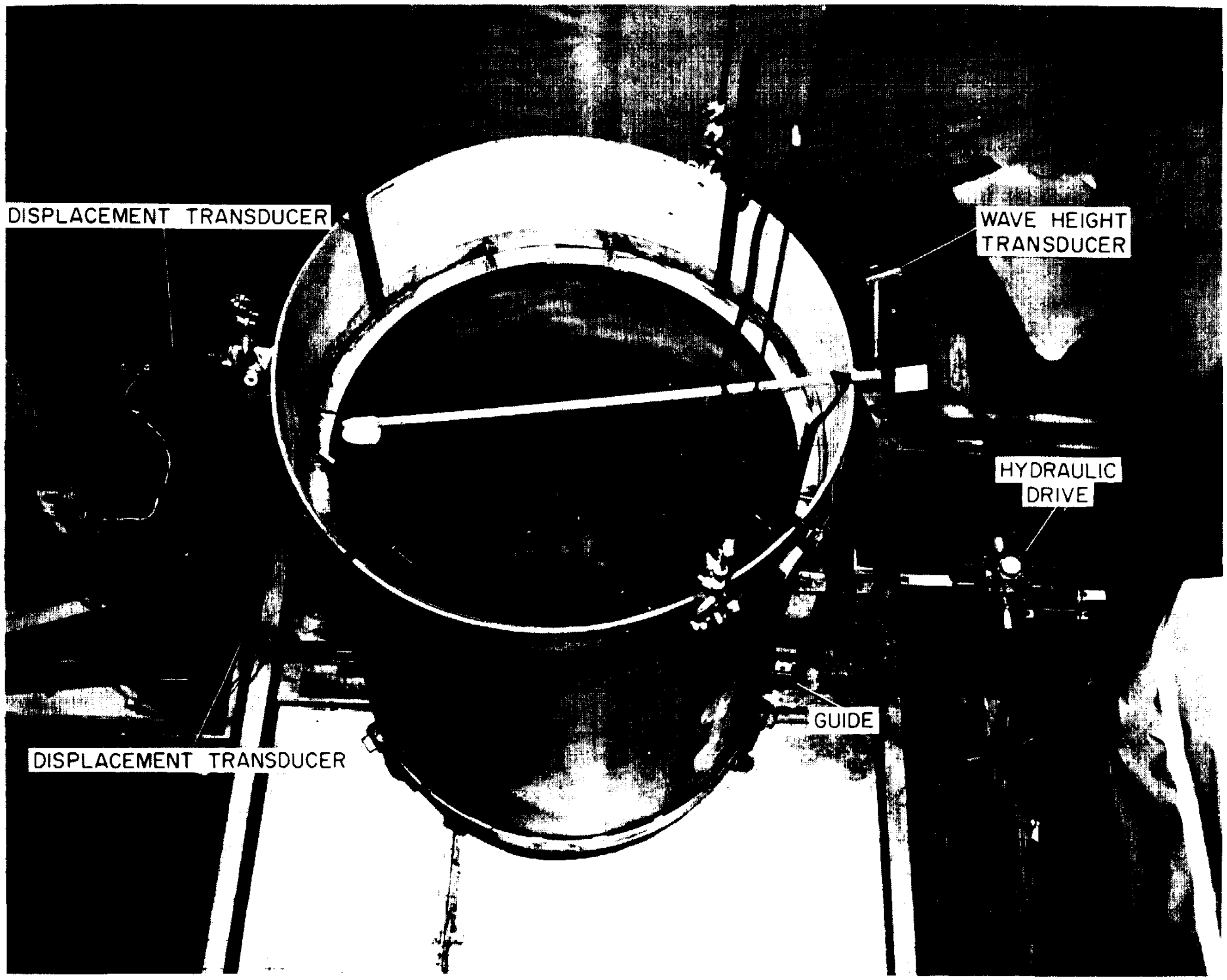

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Figure 1.- General view of test equipment.

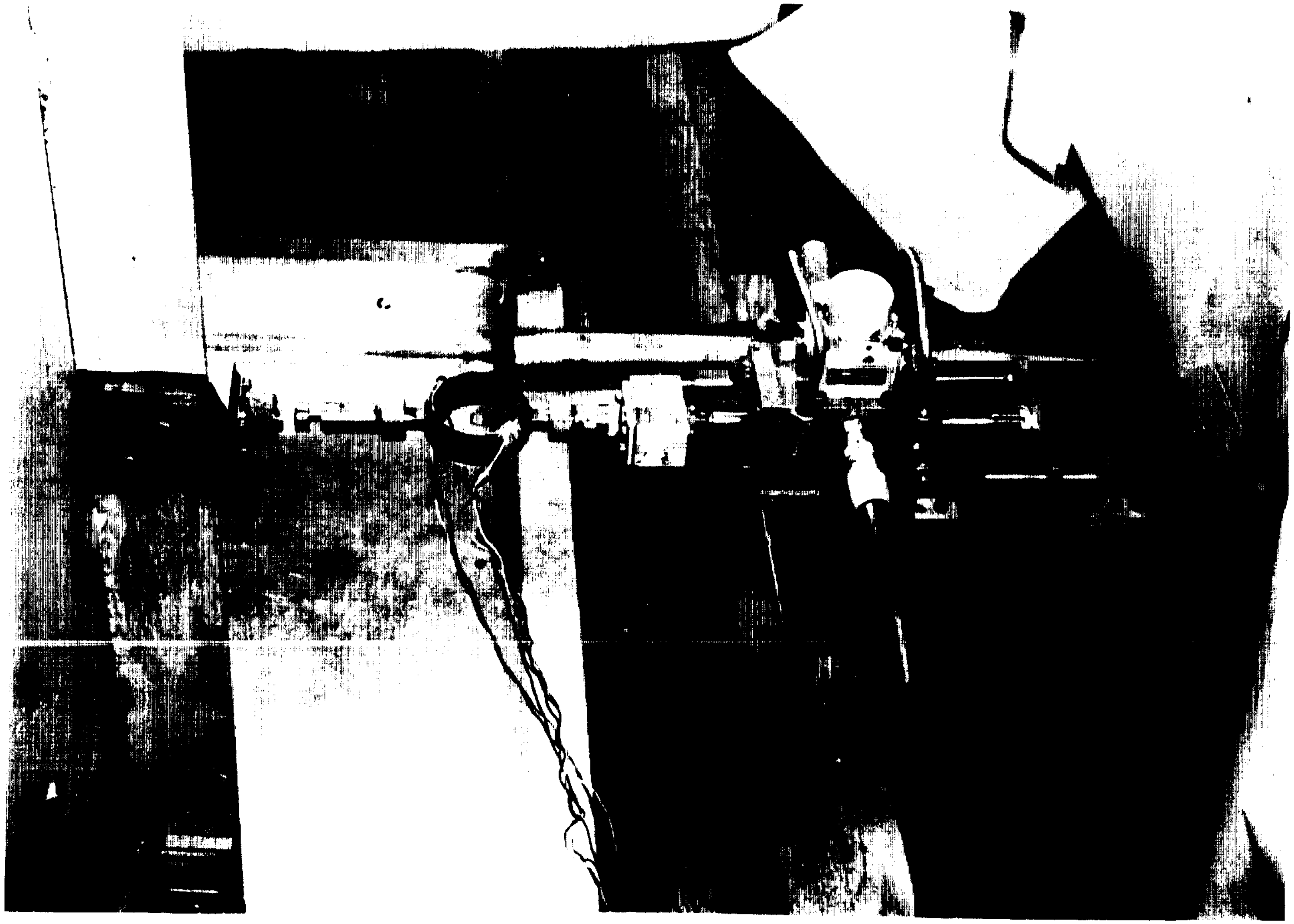

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Figure 2.- View of hydraulic servo drive and strain-gage link.

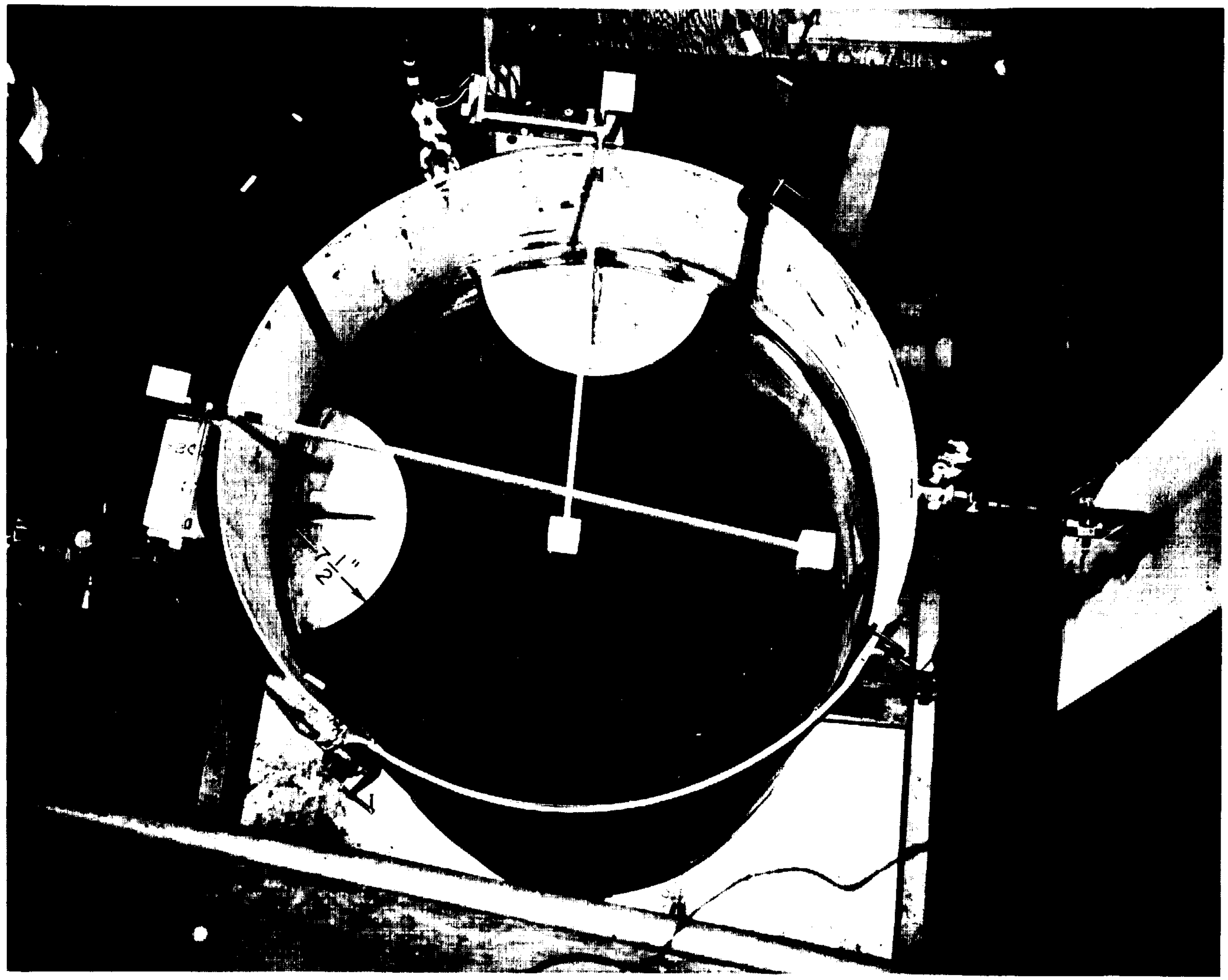

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Figure 3.- View of asymmetrical baffle.

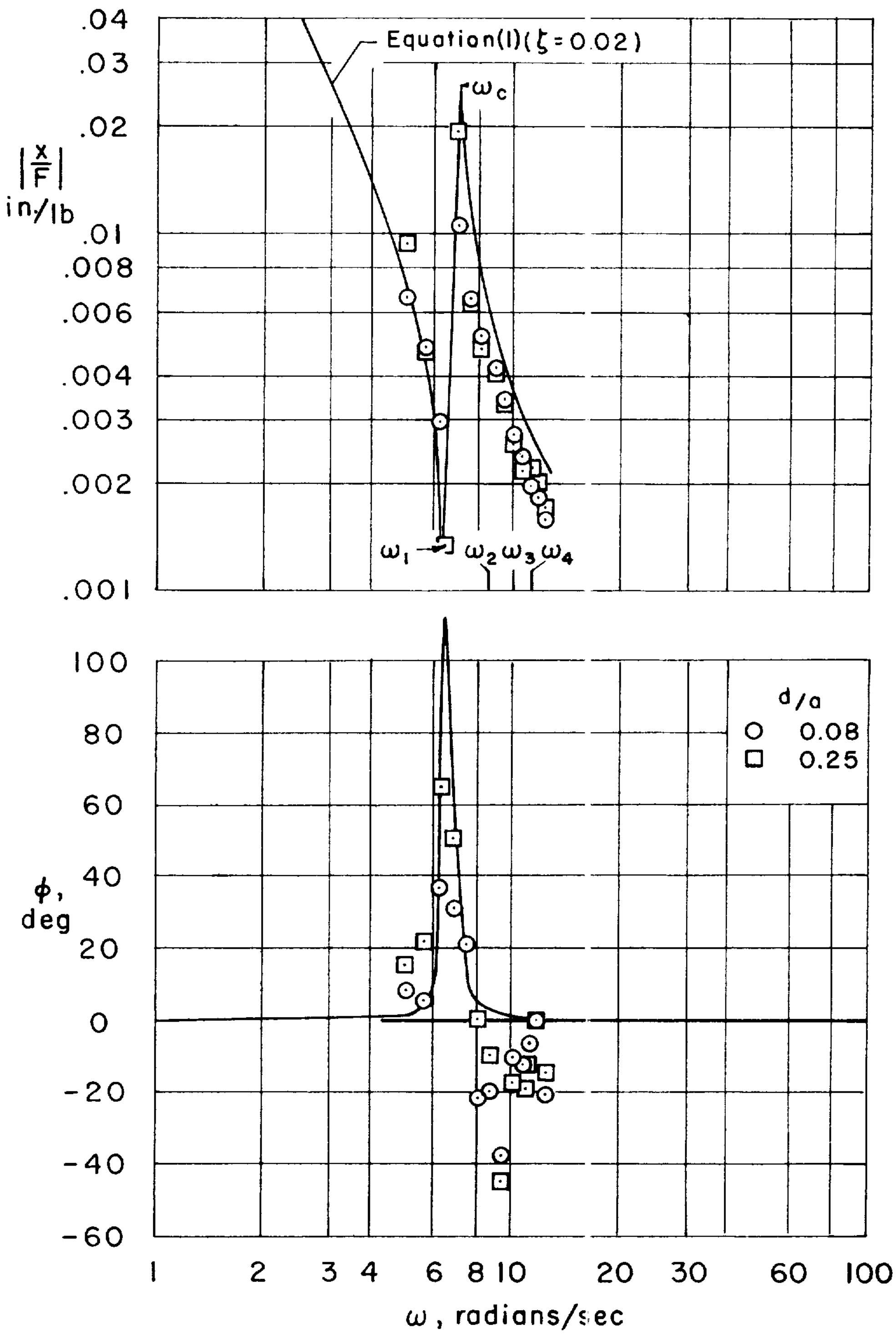

Figure 4.- Typical frequency responses for 1-1/2-inch ring, 1/16 inch thick (amplitude of x held constant at a value which gave a wave height of 3 inches at ω_1).

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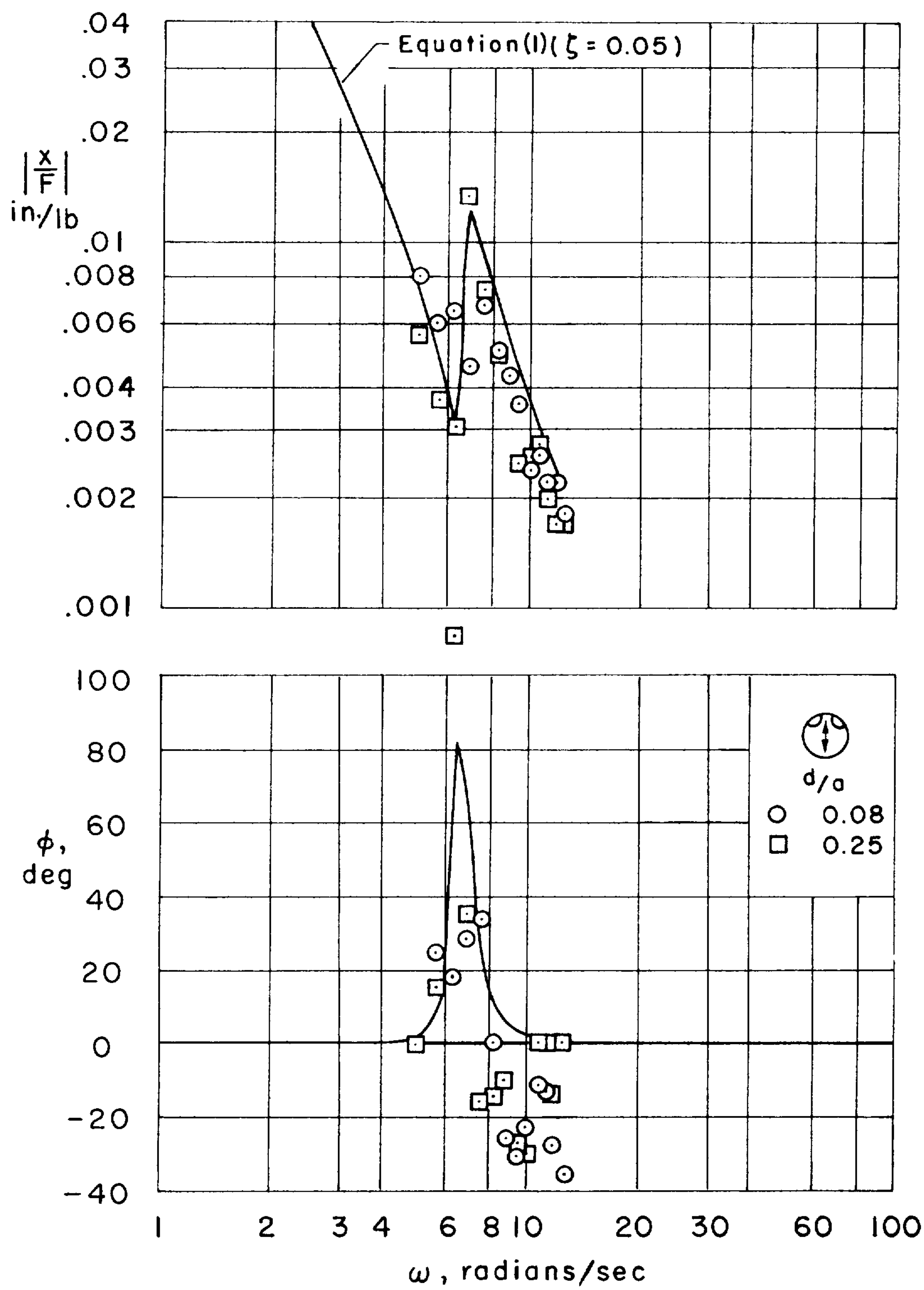

Figure 5.- Typical frequency responses for asymmetrical baffle, 1/16 inch thick (amplitude of x held constant at a value which gave a wave height of 3 inches at ω_1).

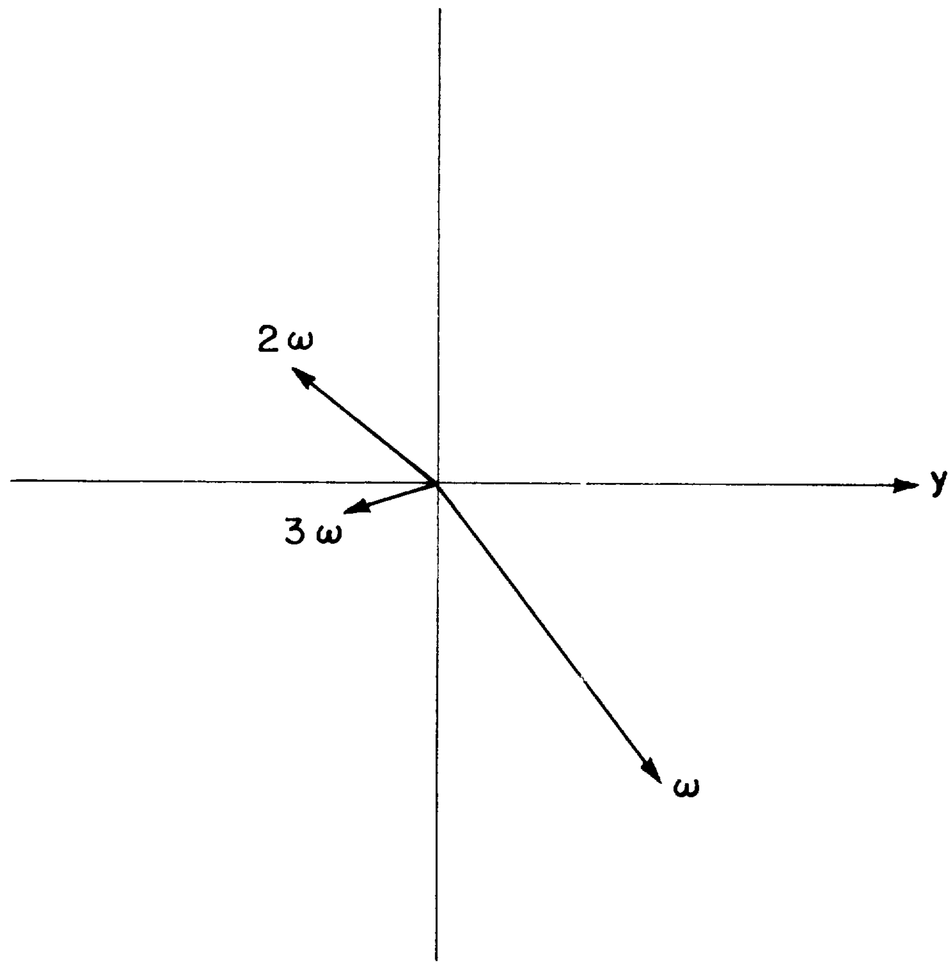

Figure 8.- Amplitude-phase plot of Fourier series components of force on a 3-inch chord baffle oscillating at a frequency of 8.6 radians/sec.

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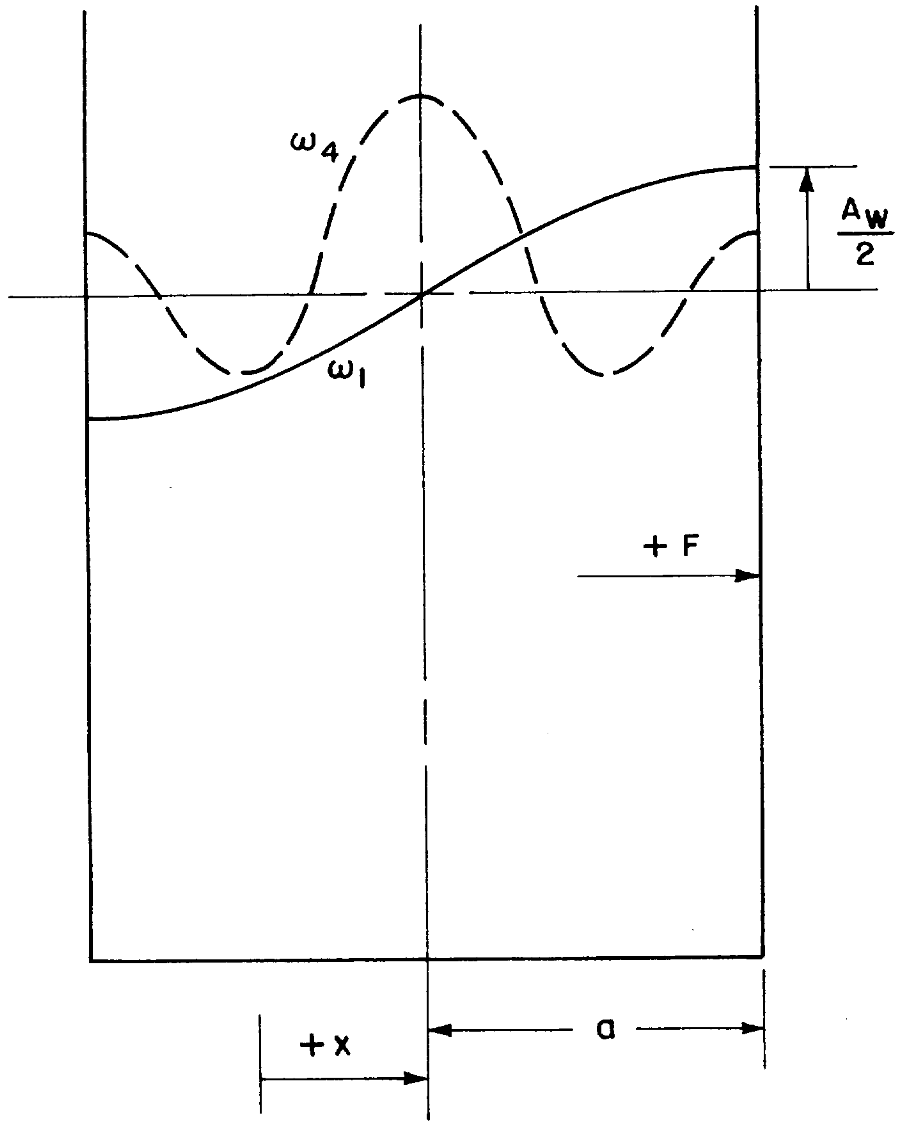

Figure 9.- First asymmetrical and second symmetrical modes in a circular basin (ω_4 = 1.95 ω_1).

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Figure 10.- Excitation of second symmetrical mode by asymmetrical baffle at $d/a = 0.25$.